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# Brief Overview of Information-gap Robustness for Decision-making

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# Outline

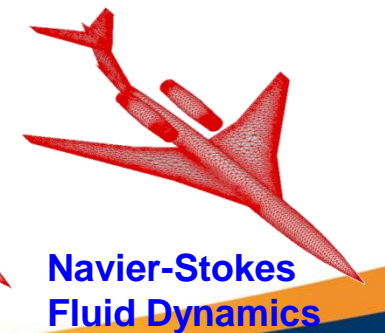
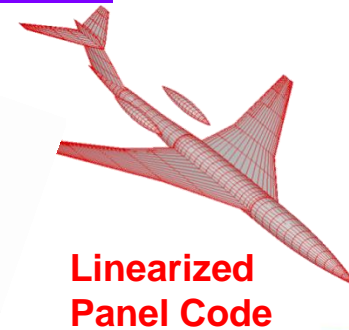
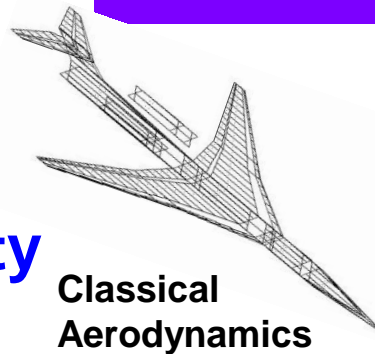
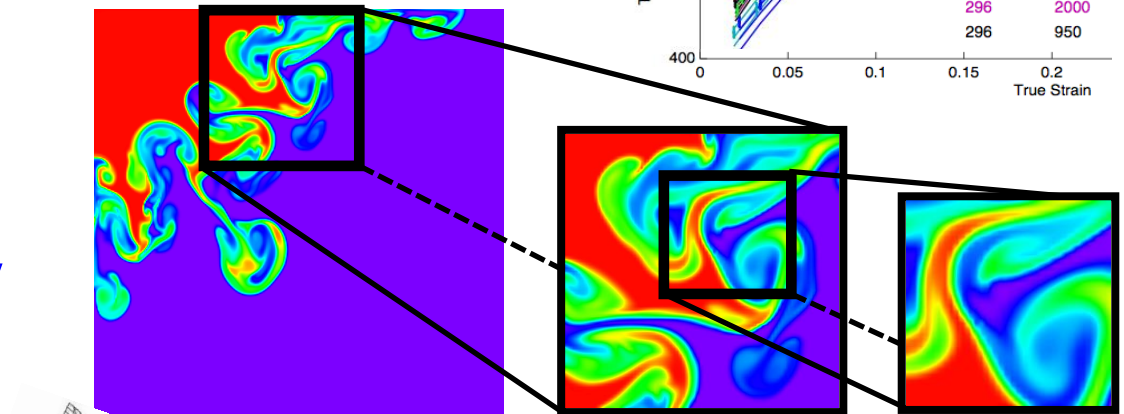
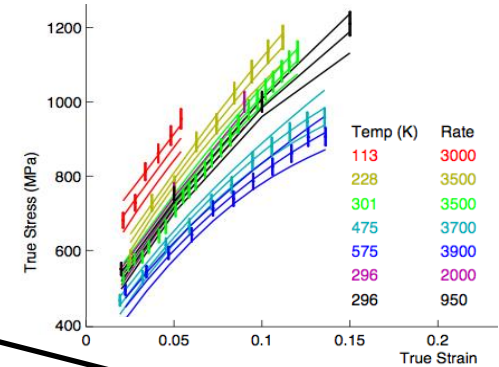
- **Brief description of info-gap robustness**
- Application to the NASA Challenge Problem
- Application to wind turbine blade vibrations

# Scientists and engineers are confronted to three broad categories of uncertainty.

- Variability and randomness

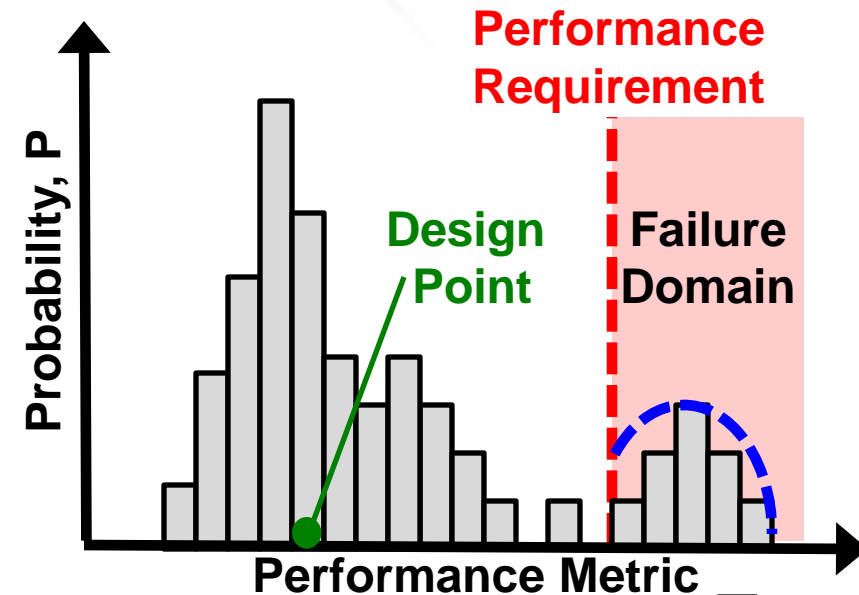
- Numerical uncertainty

- Model-form uncertainty



In the presence of uncertainty, decisions are generally made by resorting to some form or other of ***Uncertainty Quantification (UQ)***.

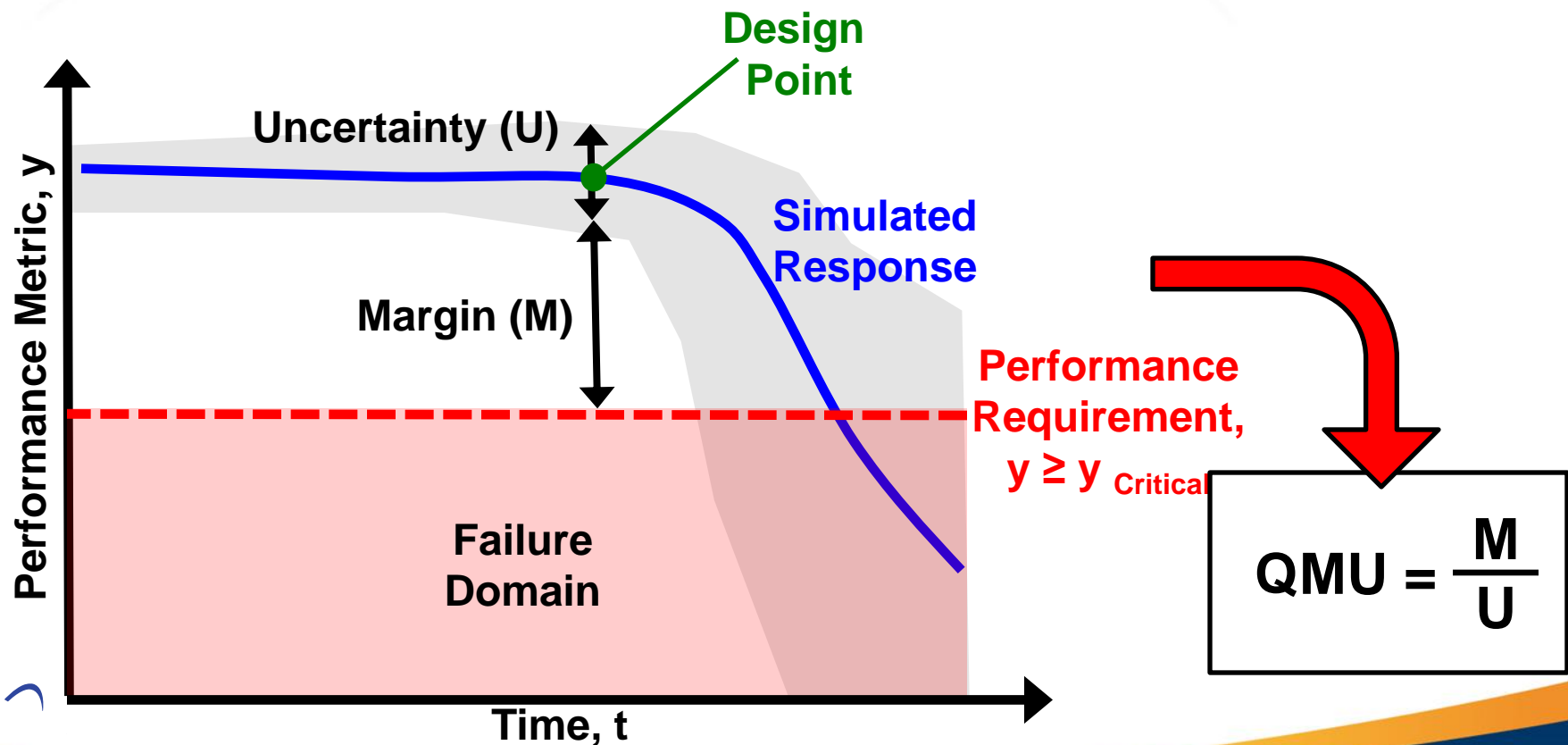
- UQ*** is the process of quantifying uncertainties associated with model predictions, with the goals of accounting for all important sources and quantifying their contributions to the overall uncertainty.
- The most common approach is to estimate the probability of failure of the system.



Probability of Failure

$$P_F = \int_{\{\text{Failure}\}} dP$$

An alternate approach to support decision-making is to establish that the system offers enough **margin**, relative to the **uncertainty** with which the performance is assessed.



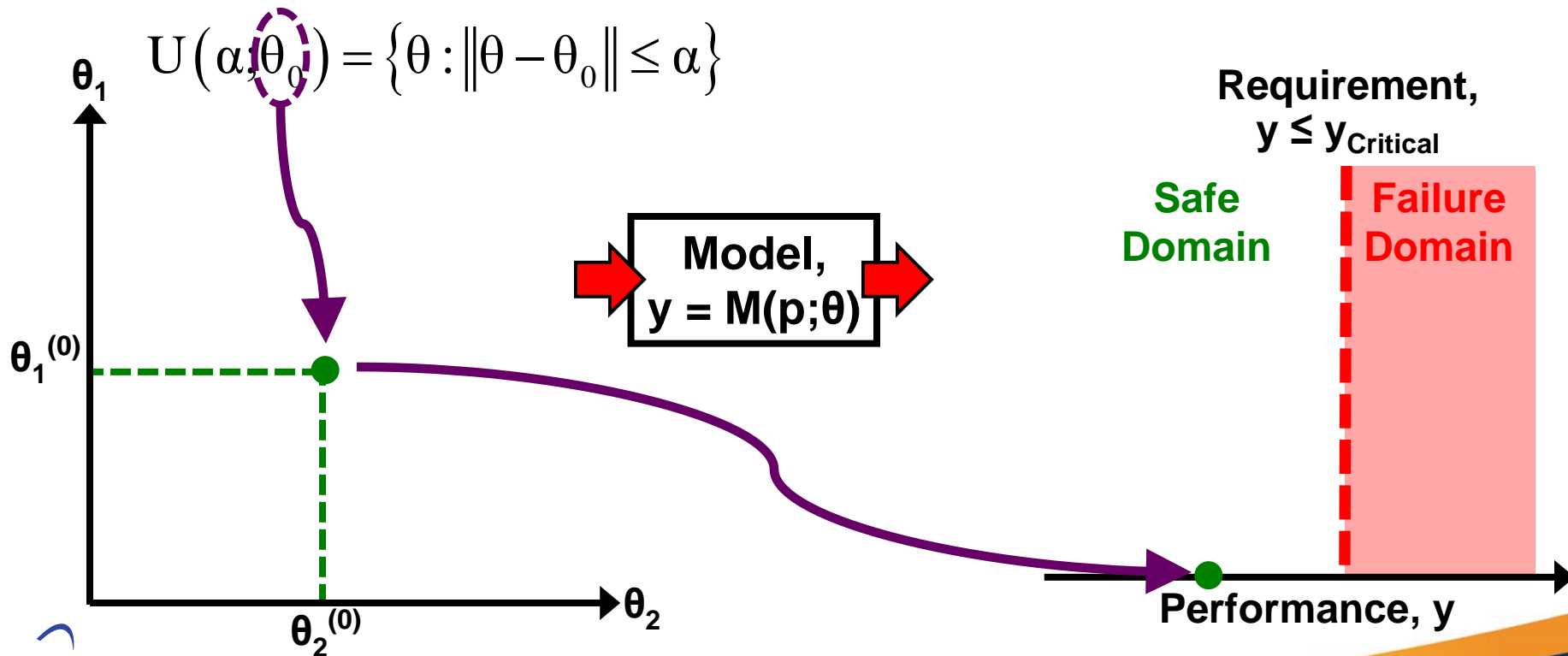
# Info-gap robustness poses a slightly different question in support of decision-making.

- Stochastic methods (i.e. probabilistic risk assessment, Monte Carlo sampling) answer the question, *“what is the probability of failure when uncertainty is propagated from variables of the model to predictions?”*
- Info-gap robustness instead answers the question, *“by how much can variables of the model deviate from their nominal settings while guaranteeing that the performance requirement is still met?”*
- A robust prediction (or decision) is one that meets the performance requirement even as settings used to perform the simulation deviate significantly from the nominal case.

An analysis of robustness makes a distinction between *design parameters*,  $p$ , and *calibration variables*,  $\theta$ , of the numerical simulation.

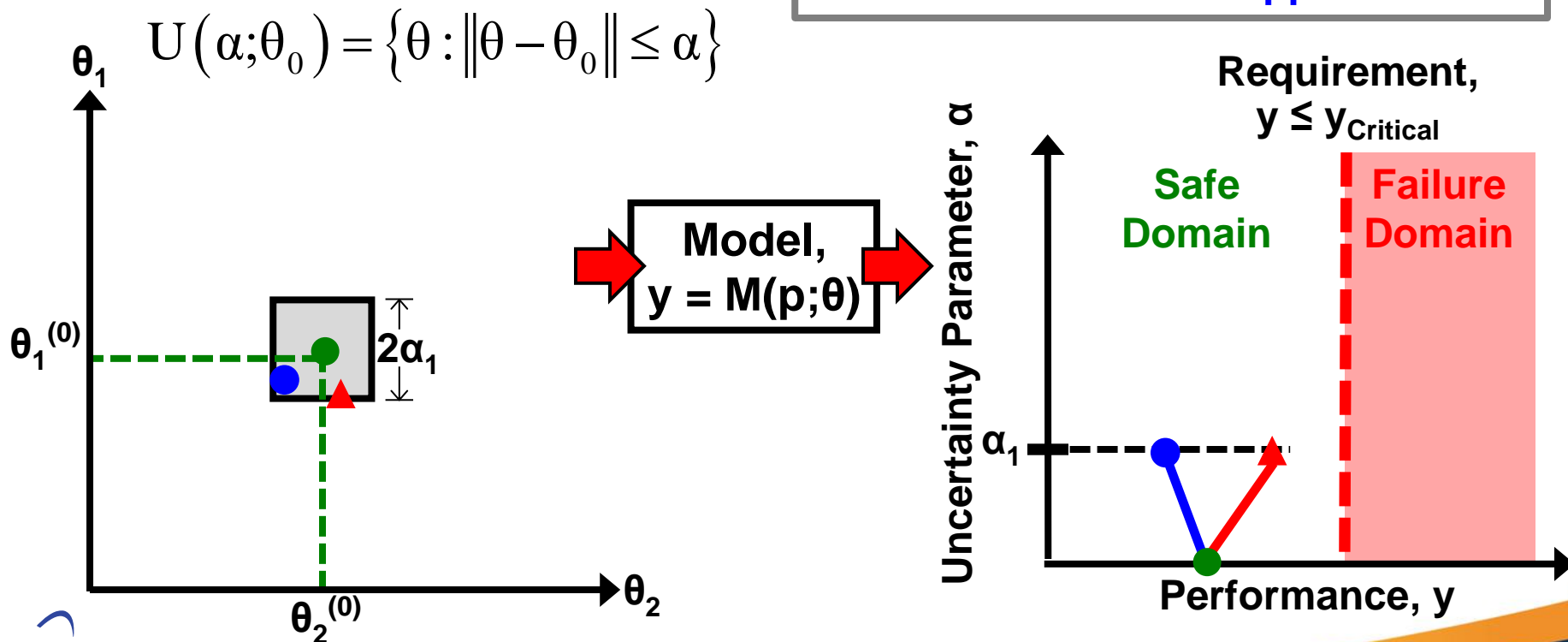
- Design parameters,  $p$ , are variables that the analyst has control over (i.e., geometry, mass, material type, ...).
- Calibration variables,  $\theta$ , are introduced by specific modeling choices (i.e., material coefficients, loads, ...).
- Uncertainty of  $p \neq$  Uncertainty of  $\theta$ .
- An analysis of info-gap robustness *explores* the design parameters to search for the best-possible design, while attempting to make the performance as *robust* as possible to the calibration variable uncertainty.

An analysis of info-gap robustness starts by evaluating the performance by executing the model at its nominal “baseline” settings,  $\theta_0$ .



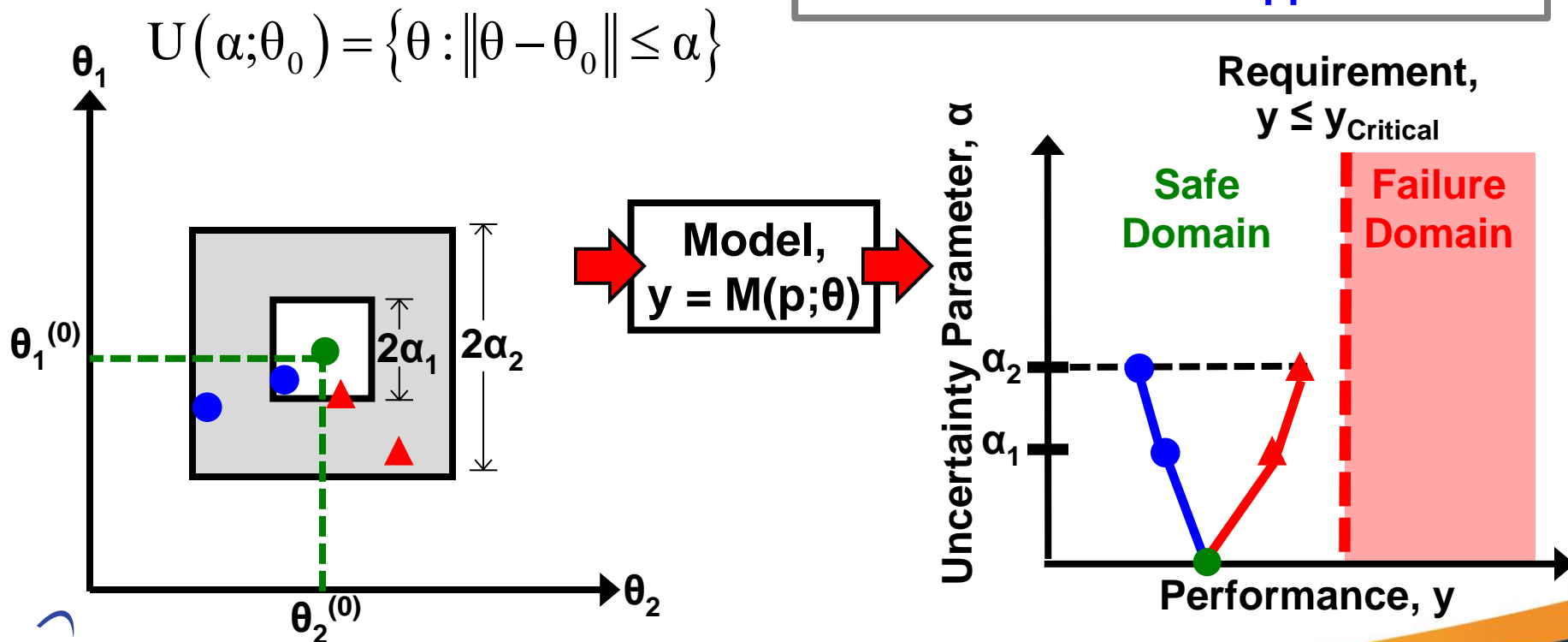
The analysis then searches for the best-case and worst-case performances as settings of the model are allowed to deviate from the nominal settings,  $\theta_0$ , up to an amount “ $\alpha$ ”.

—▲ Robustness —● Opportuneness

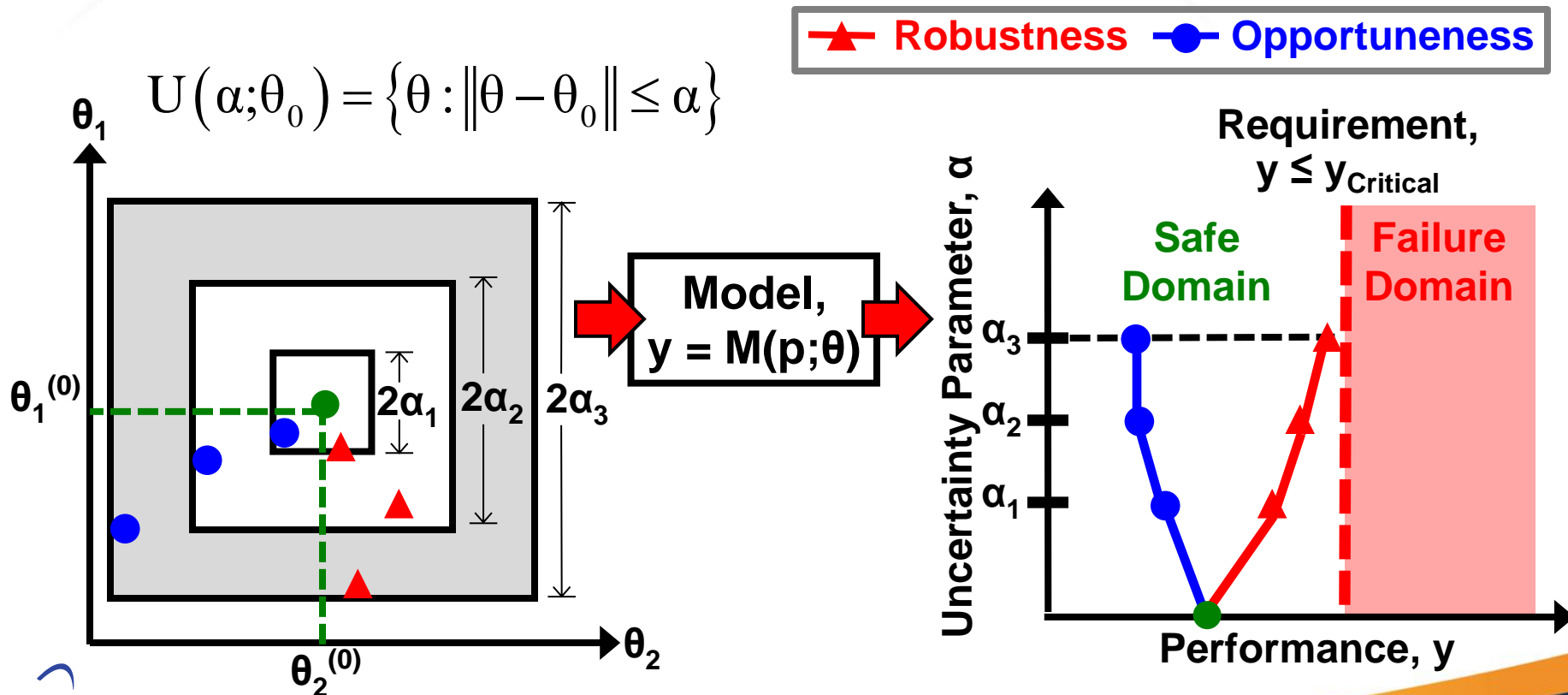


Increased levels of deviation from the nominal settings,  $\theta_0$ , are investigated by progressively increasing the uncertainty parameter  $\alpha$ , which has the effect of exploring larger spaces.

▲ Robustness ● Opportuneness



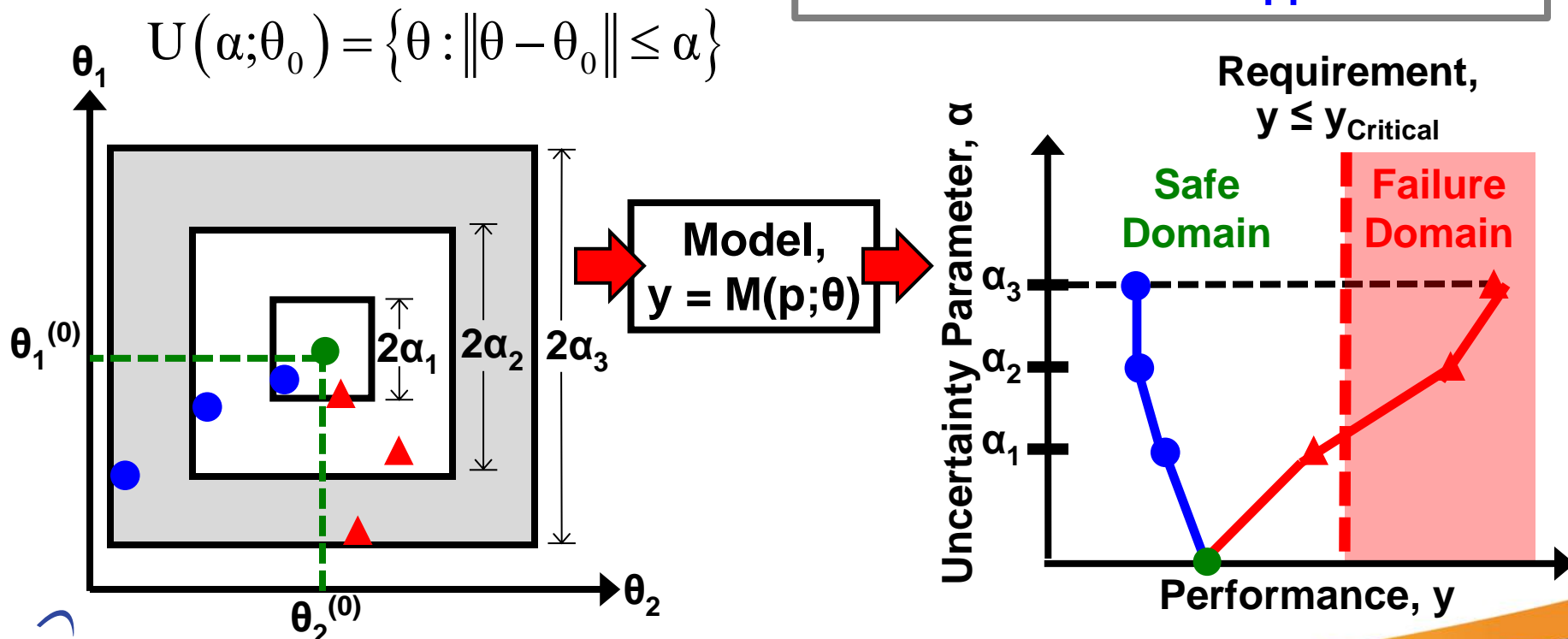
A steep robustness slope, “ $\Delta\alpha/\Delta y$ ”, indicates that the performance requirement is met even if the model is executed with settings that deviate significantly from the “baseline”  $\theta_0$ .



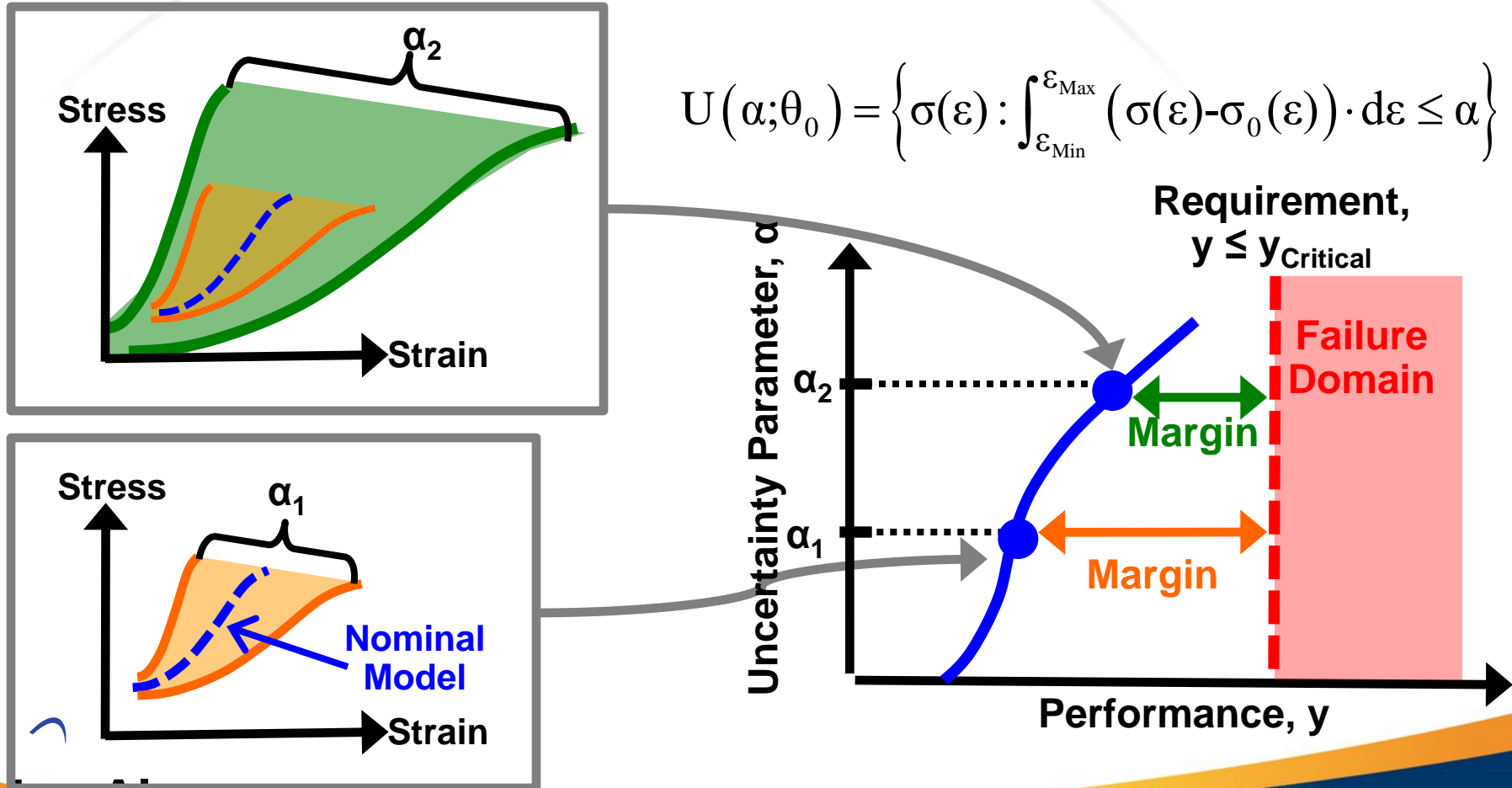
Steep Slope  $\rightarrow$  High Robustness

A moderate slope, on the other hand, points to a lack-of-robustness whereby settings of the model cannot deviate significantly from the “baseline”  $\theta_0$  before failure is reached.

—▲ Robustness —● Opportuneness



The uncertainty model,  $U(\alpha; \theta_0)$ , represents nested sets of (unknown) values or functions that are not necessarily limited to intervals.



**Summary:** An analysis of info-gap robustness assesses the extent to which the performance requirement is met, even if some settings of the model are unknown or incorrect.

- Need a performance requirement,  $y \leq y_{\text{Critical}}$
- Need a prediction model,  $y = M(p; \theta)$ .
- Need nominal “baseline” settings of the model,  $\theta_0$ .
- Need a description of uncertainty or assumptions,  $U(\theta_0; \alpha)$ .
- The uncertainty is not necessarily probabilistic.
- Requires a potentially significant computational resource.

# Outline

- Brief description of info-gap robustness
- **Application to the NASA Challenge Problem**
- Application to wind turbine blade vibrations

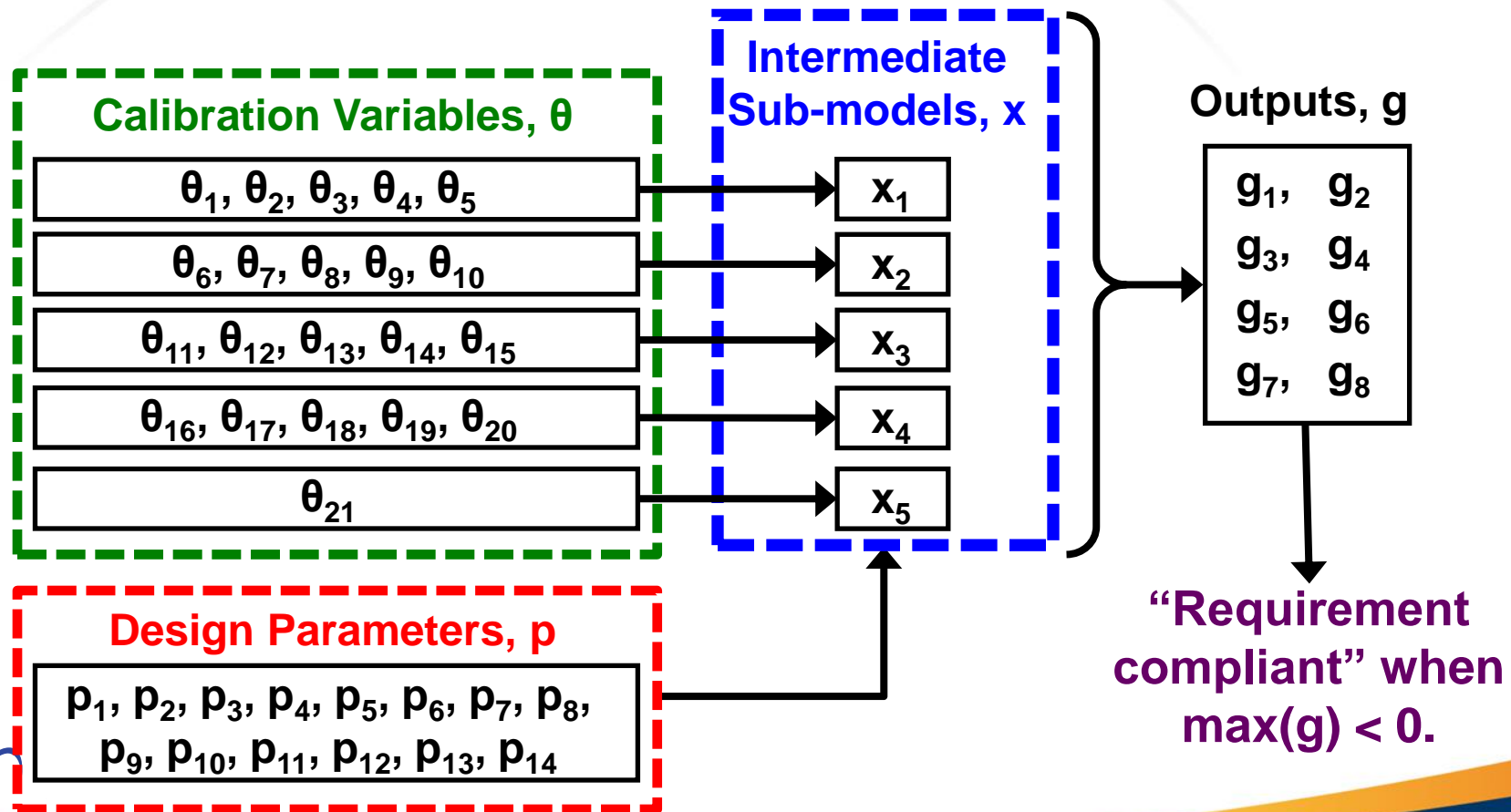
# The NASA Multidisciplinary Uncertainty Quantification Challenge Problem describes the flight dynamics of a remotely operated aircraft developed at NASA Langley.

- Multidisciplinary problem that features nonlinear aero-dynamics, atmospheric and turbulence models, avionics, engine and sensor dynamics, telemetry, time delays, and wash-out filters.
- Problem formulated to pursue model calibration, sensitivity analysis, uncertainty propagation, extreme-case analysis, and robust design.

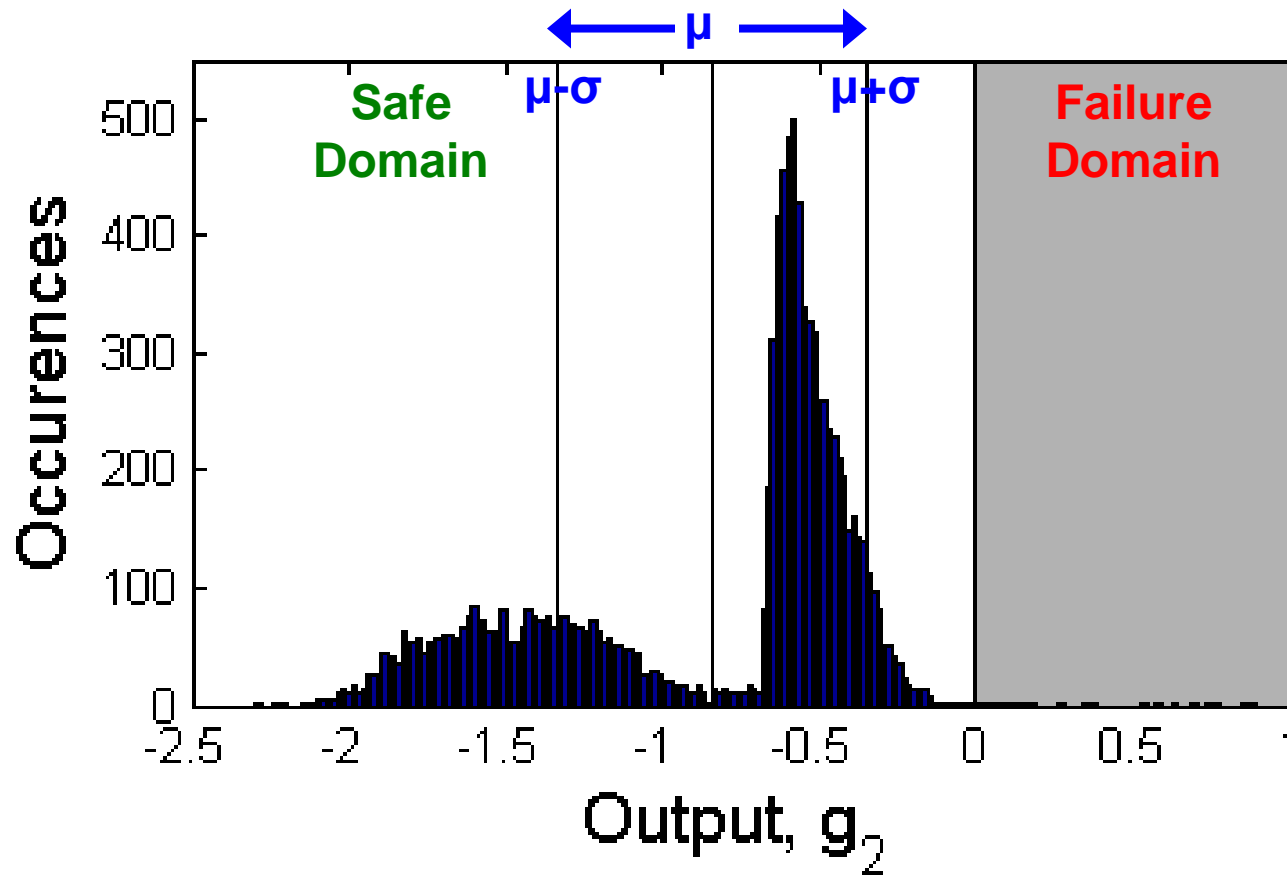


References: Jordan, T.L., Bailey, R.M., "NASA Langley's AirSTAR Testbed: A subscale Flight Test Capability for Flight Dynamics and Control System Experiments," *AIAA Guidance, Navigation and Control Conference and Exhibit*, Honolulu, HI, 2008. Crespo, L.G., Kenny, S.P., Giesy, D.P., "The NASA Langley Multidisciplinary Uncertainty Quantification Challenge," *AIAA Non-deterministic Approaches Conference*, National Harbor, MD, 2014.

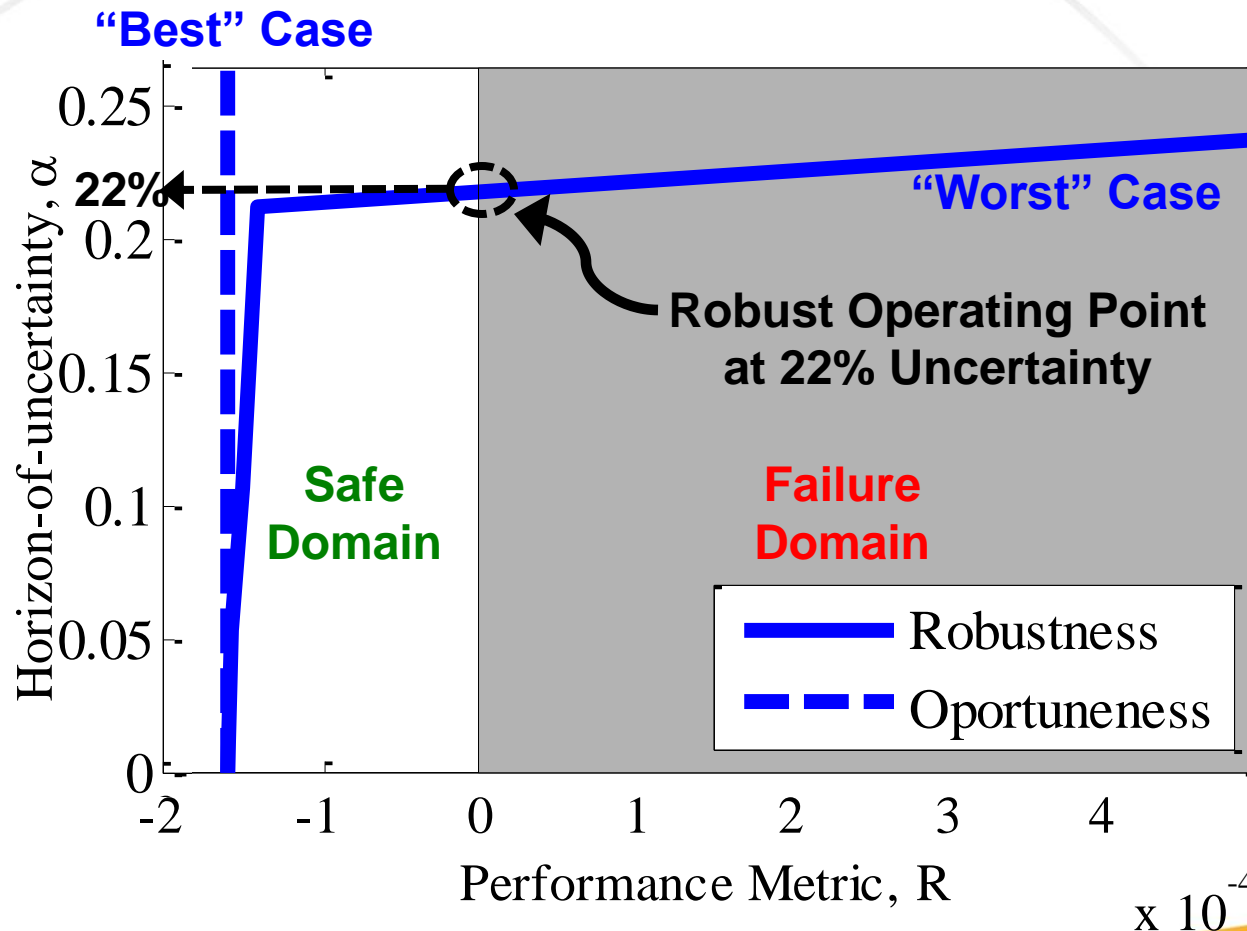
# The NASA Challenge Problem defines a high-dimensional “black-box” code developed in MATLAB<sup>®</sup>, and that depends on 35 variables.



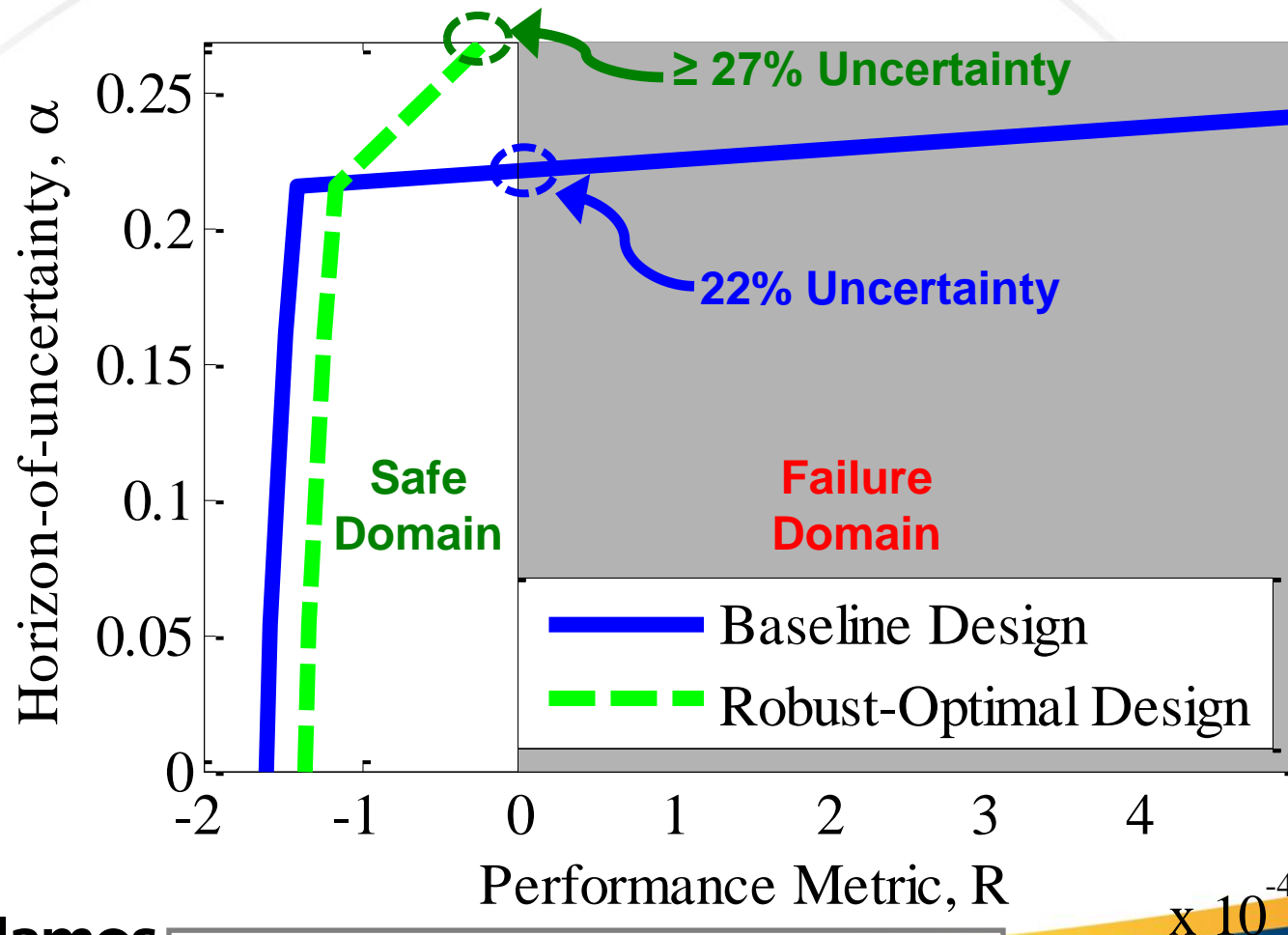
**Nonlinearity in the problem makes it difficult to use Monte Carlo-like random sampling to characterize the prediction uncertainty.**



The robustness function shows that no more than 22% calibration variable uncertainty can be tolerated before risking system failure.



Design optimization is performed by exploring parameters  $p_1 \dots p_{14}$  to maximize robustness to the uncertainty of calibration variables,  $\theta$ .



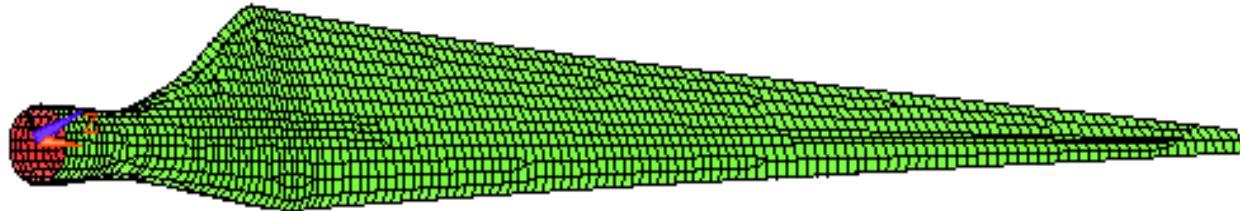
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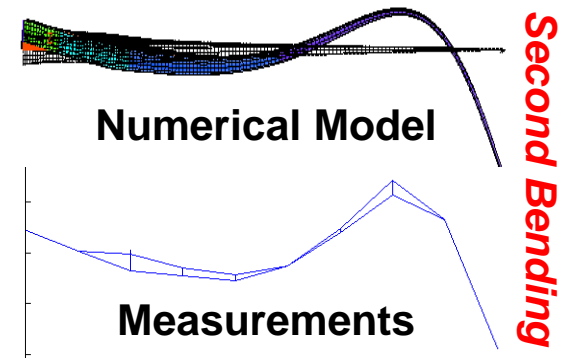
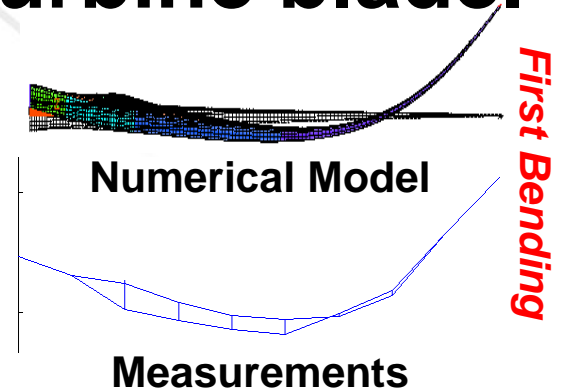
# This application selects a computational model to simulate the bending deformation of the all-composite CX-100 wind turbine blade.



**Sandia's 9-meter CX-100 Composite Blade**

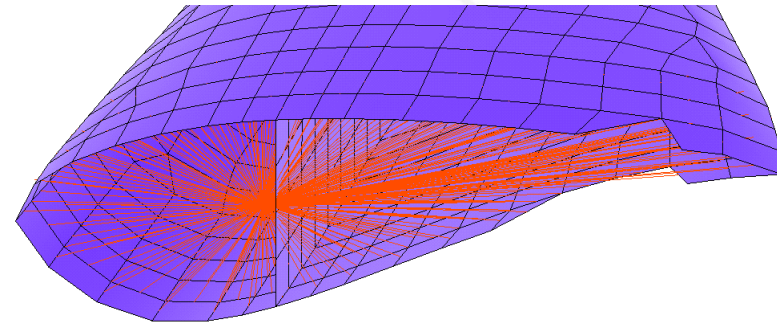
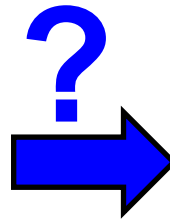


**ANSYS Finite Element Model  
(SHELL-281 Elements, 8-cm Mesh Size)**

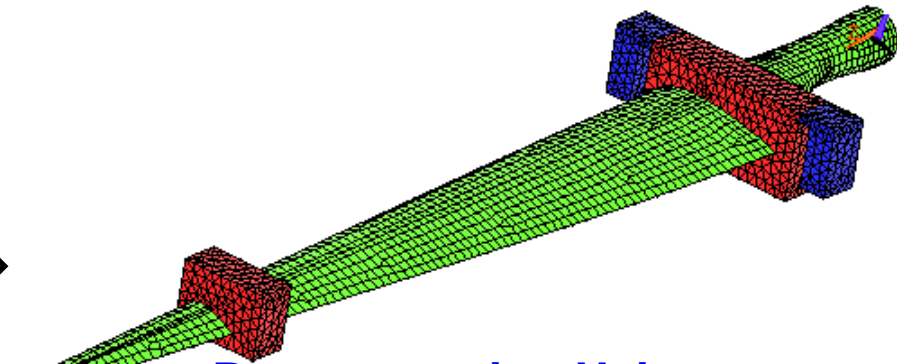
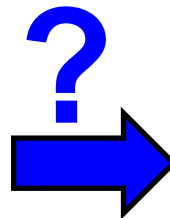


**Test-analysis Correlation**

# Two competing models are developed to simulate the vibration in a configuration of the blade that has **not** been calibrated.



Representation Using Point Masses and Stiffening Springs

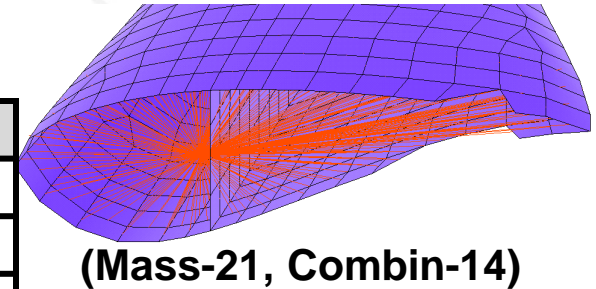


Representation Using High-fidelity Solid Elements

Each modeling strategy introduces different sets of (arbitrary) assumptions and variables whose “correct” values are unknown.

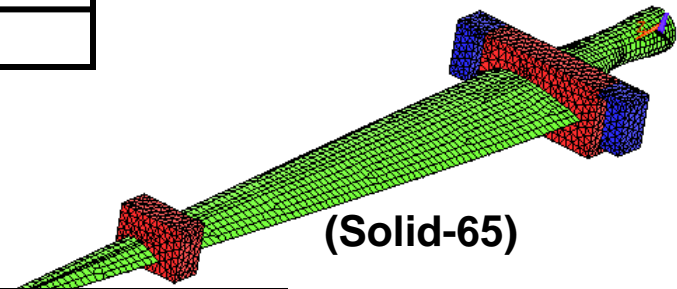
- Point-mass Parameterization:**

Unknown	Description
(1; 2)	(Translation; rotation) springs at 1.60-m section
3	Point mass at 1.60-m section
(4; 5)	(Translation; rotation) springs at 6.75-m section
6	Point mass at 6.75-m section

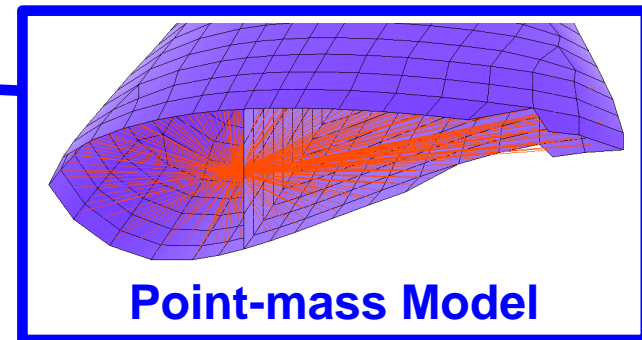
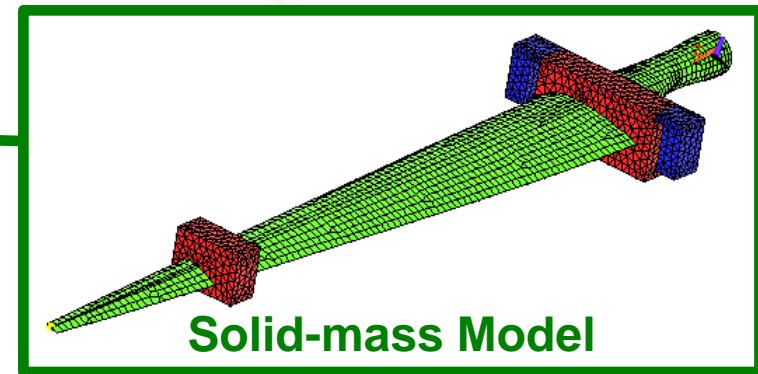
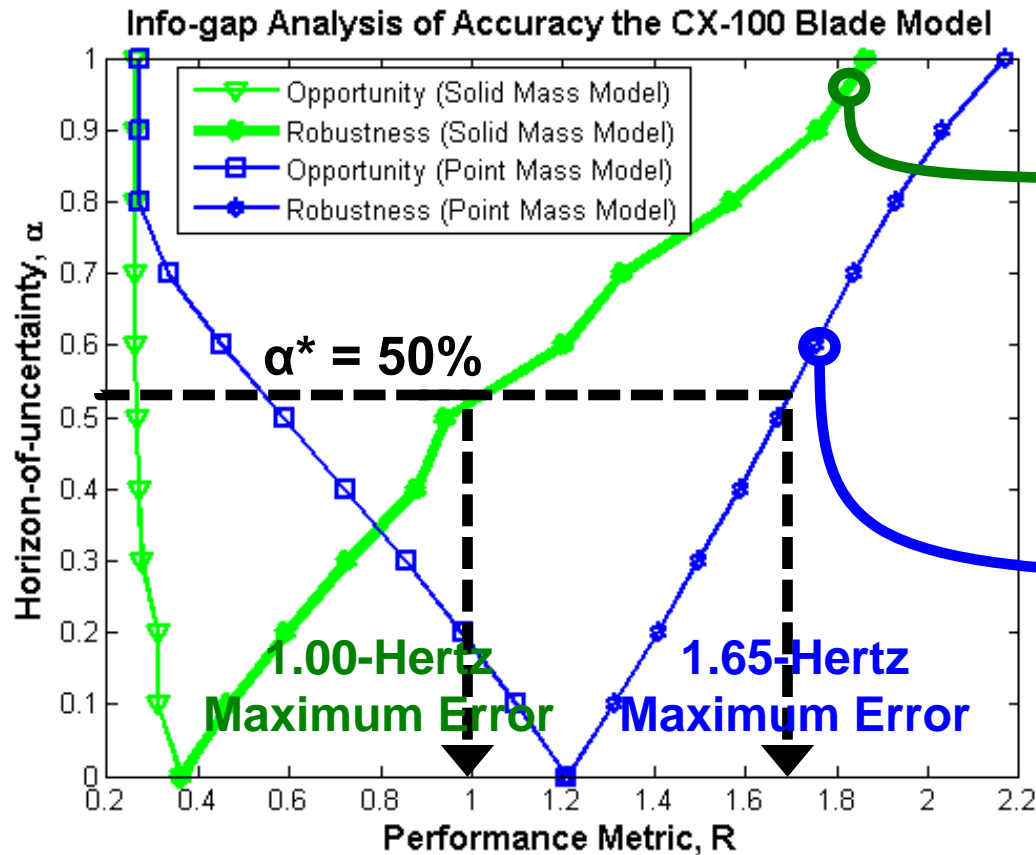


- Solid-mass Parameterization:**

Unknown	Description
(1; 2)	(Elastic modulus; density) of 1.60-m section
(3; 4)	Center-of-gravity (X; Y) coordinates of 1.60-m offset mass
5	Density of 1.60-m offset mass
(6; 7)	(Elastic modulus; density) of 6.75-m section



# The solid-mass model yields more accuracy, even when some of its parameters deviate from their “nominal” settings up to $\pm 50\%$ .



# Conclusion: Info-gap robustness offers a versatile and rigorous framework to support decision-making under severe uncertainty.

- Has been developed for 20+ years.
- Comes with a thorough theoretical framework.
- Handles various types of uncertainty in simulations or physical testing.
- Applied to problems in engineering, biology, climate modeling, economy, social behavior, etc.
- More info at <http://info-gap.com/>.

